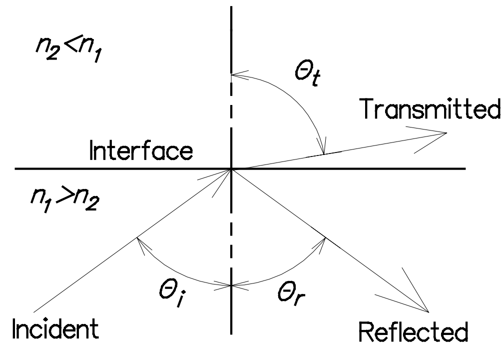
The Optical Fiber

- Overview
  - Fiber geometry
  - Fiber parameters
  - Confinement process
  - Electromagnetic modes
  - Step-index and graded-index fibers
  - Multimode and single-mode fibers

Fiber-1

Optical Confinement

- **Passing from high-index medium to low-index**
  - **$n = c/v$; n_{glass}= 1.4→1.5**



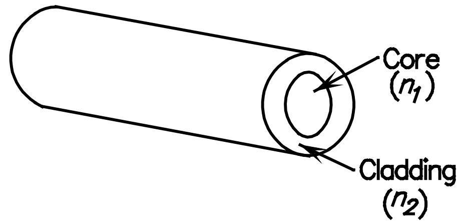
- **Snell's Law:** $\theta_t = \sin^{-1}(n_1 \sin\theta_i / n_2)$

- **If angle of incidence exceeds critical angle,** $\theta_c \equiv \sin^{-1}(n_2/n_1)$
  - **Total internal reflection**
    - » **Light reflects at interface with *NO* loss**
    - » **Light guided down fiber**

Fiber-2

Fiber Geometry & Step-Index Profile

- Geometry (left)
  - Core
  - Cladding
  - Buffer (outside cladding)
  - Jacket

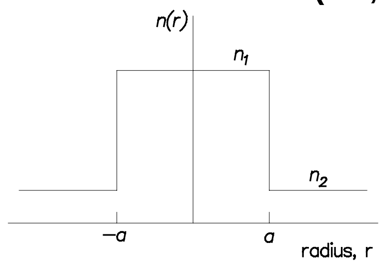


- Refractive-index profile
  - Abrupt change at core-cladding interface

    $n_2 \approx n_1(1-\Delta)$

    Δ is "fractional change of *n*" $\Delta = n_1^2 - n_2^2 / 2n_1^2 \approx (n_1 - n_2)/n_1$

  - Typical values of Δ: 0.001→0.02 (i.e., 0.1% to 2%)



Fiber-3

Representative Fiber Parameter Values

Table 2.1, p.20

Type	Core diam µm	Cladding diam µm	Δ
8/125 SM	8	125	0.1-0.2%
50/125 MM	50	125	1-2%
62.5/125 MM	62.5	125	1-2%
100/140 MM	100	140	1-2%

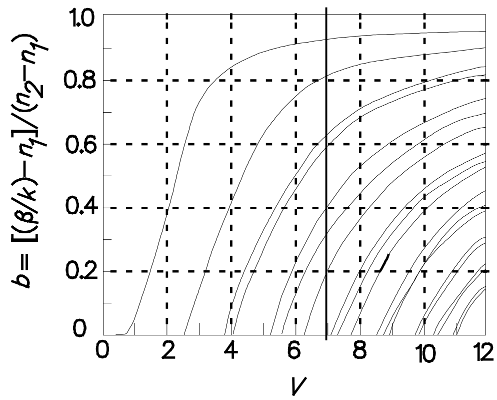
Step Index (SI) Fibers: Waveguide Modes

- **Cylindrically-symmetric dielectric waveguides**
- **Model and solve for the electromagnetic fields**
- **Certain characteristic electromagnetic *modes* can propagate**
  - **Simplest modes**
    - » **Modes with radial symmetry**
    - » **TE (transverse electric)**
    - » **TM (transverse magnetic)**
  - **Hybrid modes also exist**
    - » **Combinations of TE and TM**
    - » **HM_{mn} and EH_{mn} modes**
  - **Linearly polarized**
    - » **LP_{mn} modes**
- **Each mode has its own propagation constant**

Mode Behavior

- **Fiber *V*-parameter:** $V = (2\pi a/\lambda)\sqrt{n_1^2 - n_2^2} \approx (2\pi a n_1/\lambda)\sqrt{2\Delta}$
- **Each mode has own velocity**

Relative velocity



- ***V* < 2.405**
  - **Single mode exists**
  - ***Single-mode fiber***

- ***V* > 2.405**
  - **Many modes exists**
  - ***Multimode fiber***
  - ***Usually, V >> 2.405***

Fiber-6

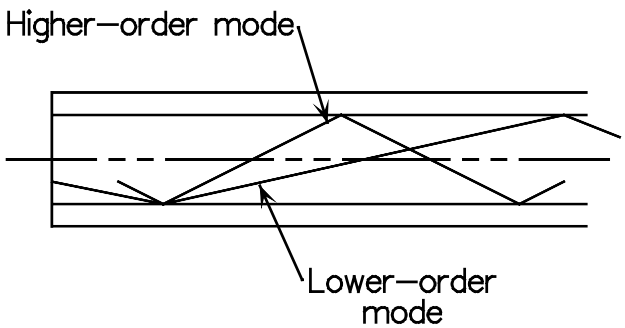
- V-parameter used to describe modes
- V-parameter equation
  - ☞ *a* is core radius
  - ☞ λ is free-space light wavelength
  - ☞ n_1 and n_2 are the core/cladding indices

Multimode Step-Index Fibers

- **Number of modes**:

$$N \approx V^2/2 \approx \left(2\pi a\, n_1/\lambda\right)^2 2\Delta \qquad (V >> 2.405)$$

- **Ray representation of multiple modes**
  - **High-order modes: Steep incidence (close to θ_c)**
  - **Low-order modes: Low grazing angles**



  - **Ray picture *not* appropriate for few modes or single mode**
- **Mode coupling (*mode mixing*) possible due to interface inhomogeneities**
- **Measurements of multimode phenomena require uniform excitation of all modes**

Fiber-7

Power Distribution Between Core and Cladding

- Cladding field is not zero!
  - Mode's power carried in *both* core and cladding

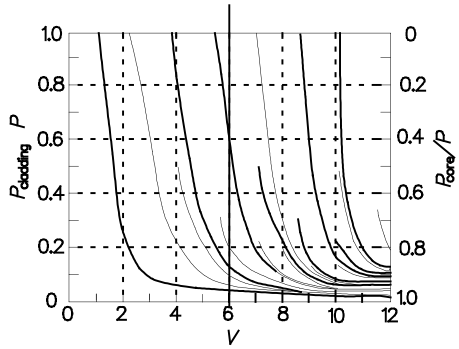


Fig. 2.6, p. 25

- **Fraction of total optical power in cladding**:

$$P_{\text{cladding}} / P_{\text{core}} \approx 4/3\sqrt{N} \qquad (\text{for } V >> 2.405)$$

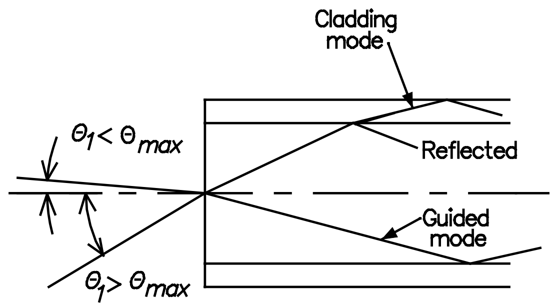
(*N* is number of modes)

- **For small *V*, large fraction of power is in cladding. Avoid this!**

Fiber-8

SI Fibers: Numerical Aperture (NA)

- **Coupling light into fiber**
  - **Only certain rays are accepted by fiber**
  - **Ray at θ_c at core/cladding interface**
    - **Is at θ_{max} at air/fiber input**



- **Input rays**
  - ***Less* than θ_{max} are guided**
  - ***Greater* than θ_{max}, are not guided**
- ***Numerical aperture***

$$\mathrm{NA} \equiv \sin\theta_{\max} = \sqrt{n_1^2 - n_2^2} \approx n_1\sqrt{2\Delta}$$

Fiber-9

- Ex.: 50/125 fiber, n_1 =1.49, Δ = 1.5% ⇨ θ_{max} = 14.96º, NA =0.258

Cladding Modes and Leaky Modes

- ***Cladding modes***:
  - Light carried in cladding
  - Remove with ***mode stripper***

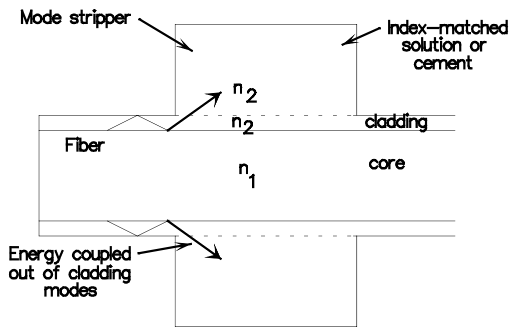


Fig. 2.8, p. 28

- ***Leaky mode***:
  - Nonpropagating mode with power shared between core and cladding
  - Difficult to predict and model
- **Short-distance links can carry significant power in unguided modes and cladding**

Step-Index Single-Mode (SI-SM) Fibers

- For $V < 2.405$
  - Only one mode propagates $\Rightarrow$ ***single-mode fiber***
- Generally,
  - **Small core radius** (2 to 5 μm)
  - **Small Δ** (typically, <1%)
- Superior performance (over multimode fibers) for carrying high data-rate signals
  - ***The*** **fiber of choice!**

Fiber-11

- Mode is actually "doubly degenerate" (i.e., two orthogonal polarizations propagate), but still called a single mode

SM Fibers: Cutoff Wavelength and Power Distribution

- ***Cutoff wavelength*** **(theoretical)**
  - ***V*** **is function of** λ
  - **Value of** λ **that makes** ***V*** **= 2.405 (step index fiber)**

$$V_{\text{cutoff SI}} \equiv 2.405 = \frac{2\pi a n_1}{\lambda_{cutoff}}\sqrt{2\Delta}; \quad \Rightarrow \quad \lambda_{cutoff} = \frac{2\pi a n_1}{2.405}\sqrt{2\Delta}$$

  - **Actual cutoff wavelength**
    - » **Susceptible to variations in fiber parameters**
    - » **Usually measured**

- ***Power distribution***
  - **At** ***V*** **= 2.405:** $\approx$ **84% of mode's power in core**
  - **At** ***V*** **= 1:** $\approx$ **30% in core (power at risk of being lost)**
  - **Do not want** ***V too*** **small**
    - » **Design compromise:** **2.0 <** $V_{SM\ SI}$ **< 2.405**

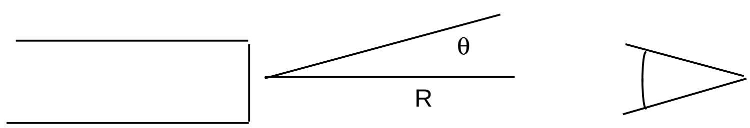
Fiber-12

SM Fibers: Mode Field Diameter

- Wave in SM fiber
  - Ray model *not* appropriate
  - Assumed mode in 1970s and 1980s: Gaussian shaped
    - » Modern fiber fields *not* Gaussian shape
  - Part of wave in core; part in cladding
    - » *a* does not describe "width" of wave
- ***Mode field diameter (MFD)*:**
  - Useful measure of field width
  - Unfortunately, mathematically defined several ways
- MFD used to predict
  - Coupling losses
  - Splice losses
  - Connector losses
  - Propagation effects
  - Other effects in SM fibers

SM Fibers: MFD Definitions

- **Circular fiber geometries assumed**
- **Measure field distributions**
  - ***Near-field optical amplitude distribution*, *e(r)***
  - ***Far-field amplitude distribution E(ρ)***
    - » **$\rho = 2\pi \sin \theta/\lambda$**
  - **Distributions are mathematically interrelated by the Hankel transform**
- **$|e(r)|^2$ and $|E(\rho)|^2$ are light *intensity* distributions**
- **MFD defined from measurement of near-field or far-field intensity patterns**



- Distributions are related by $E(R,\rho) = \dfrac{k\cos\theta}{iR}\exp(ikR)\int_0^\infty e(r)J_0(r\rho)\,r\,dr$

☞ R is observation distance from fiber end ($R \gg r^2_{max}/\lambda$)
☞ $\rho = k \sin\theta$

- Neglecting cos θ term,

$$E(\rho) = \int e(r)J_0(r\rho)\,r\,dr = \frac{1}{\sqrt{2\pi}}H\{e(r)\}$$

◆ *H{ }* is Hankel-transform operator

☞ Far-field angular distribution *E(ρ)* is Hankel transform of near-field distribution

$$E(\rho) = \int_0^\infty e(r)J_0(r\rho)r\,dr = H\{e(r)\}/\sqrt{2\pi}$$

Fiber-14

SM Fibers: MFD Definitions (cont.)

- **MFD I: *Near-field MFD* (or *Petermann I MFD*):**

$$d_n = 2\sqrt{2}\sqrt{\frac{\int_0^\infty e^2(r)r^3 dr}{\int_0^\infty e^2(r)r\, dr}}$$

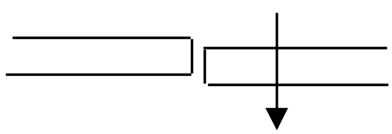
- **MFD II: *Far-field MFD* (or *Petermann II MFD*):**
  - **Adopted as *the* international standard**

$$d_f = 2\sqrt{2}\sqrt{\frac{\int_0^\infty E^2(\rho)\rho^3 d\rho}{\int_0^\infty E^2(\rho)\rho\, d\rho}}$$

- **MFD III: Transverse-offset MFD**
  - **Growing out of favor, but easy to measure**
  - **Two identical butt-coupled single-mode fibers**
  - **Laterally displace one; measure transmitted power**
  - **MFD (d_a) = offset when power is *1/e* times initial power**

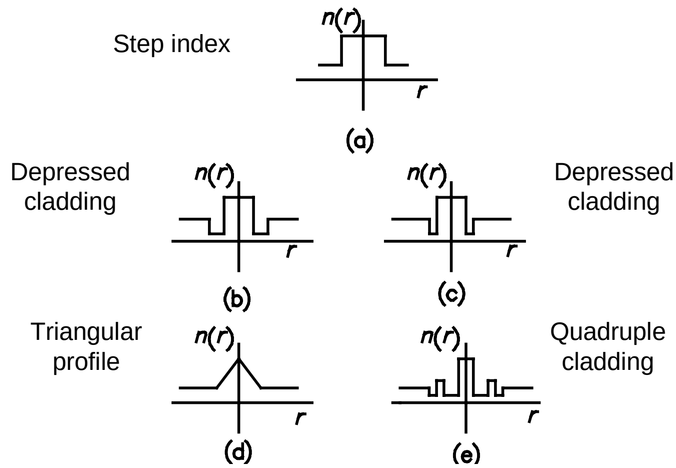
Fiber-15

- Transverse offset measurement



Multi-Step Single-Mode Fibers

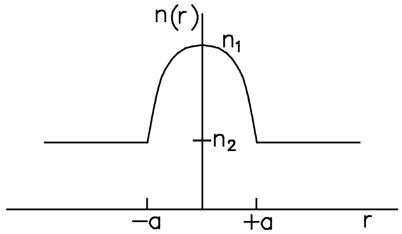
Fig. 2.9
p. 35



- **Pros: increased data rates, less loss susceptibility, more fiber design flexibility**
- **Cons: harder to fabricate, harder to model**

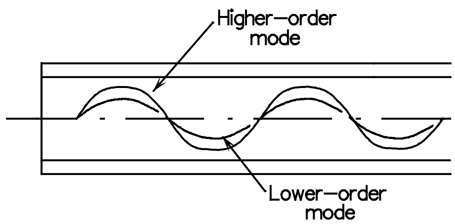
Graded-Index Multimode (GI MM) Fibers

- **Non-step-index profile *n(r)***



$$n(r) = \begin{cases} n_1\sqrt{1-2\Delta(r/a)^g} & r \le a \\ n_1\sqrt{1-2\Delta} \approx n_1(1-\Delta) = n_2 & r \ge a \end{cases}$$

- **Wave confinement by sinusoidal path within core**



- **Cladding**
  - **Only isolates core from outside world**
  - **No guiding action**

Fiber-17

Graded-Index Profiles

- **Power-law profile model**

$$n(r) = \begin{cases} n_1\sqrt{1-2\Delta(r/a)^g} & r \le a \\ n_1\sqrt{1-2\Delta} \approx n_1(1-\Delta) = n_2 & r \ge a \end{cases}$$

  - ***n_1*** **: refractive index at core center**
  - ***n_2*** **: refractive index at core edge and in cladding**
  - Δ **: fractional change in index (core center to edge)**

$$\Delta = \left(n_1^2 - n_2^2\right) / 2n_1^2 \approx \left(n_1 - n_2\right)/n_1$$

    - » **Same definition as SI**
    - » $\Delta \approx$ **1% to 2%**

- ***Profile parameter*** **or** ***gradient, g***
  - ***g*** **= 2: parabolic profile (Close to optimum for max data rate)**
  - ***g*** **= 1: triangular profile**
  - ***g*** **= ∞: step-index profile**

GI Fibers: Number of Modes and NA

- **V-parameter (for typically small Δ):**

$$V \approx (2\pi n_1 a/\lambda)\sqrt{2\Delta} \qquad \text{(same as SI)}$$

- **Number of modes *N* :**

$$N_{\mathrm{GI}} \approx \left(\frac{4a^2\pi^2 n_1^2 \Delta}{\lambda^2}\right)\left(\frac{g}{g+2}\right) = \left(\frac{V^2}{2}\right)\left(\frac{g}{g+2}\right) = N_{\mathrm{SI}}\left(\frac{g}{g+2}\right)$$

- **Numerical aperture**
  - **GI fiber NA more difficult to define than SI fiber NA**
  - **Maximum acceptance angle Θ_{max} is function of radial position of ray entry location.**
  - ***Local NA*:**

$$\mathrm{NA}(r) = \begin{cases} \mathrm{NA}(0)\left[1-(r/a)^g\right] & \text{for } r < a \\ 0 & \text{for } r \geq a \end{cases}$$

    - » **NA(0): NA at core center = sqrt(n_1^2-n_2^2)**

Fiber-19

- Ex.: 50/125 GI fiber, g = 2, Δ = 1.34%, λ = 850 nm $\Rightarrow$ N = 504 modes

Single-Mode Graded-Index (SM-GI) Fibers

- Can make SM-GI fibers
  - Triangle profile
  - Parabolic profile
- Cutoff location

$$V_{\text{cutoff}} \approx 2.405\sqrt{1+(2/g)}$$

  - Estimate:
    - » V_{cutoff} (triangle) = 4.38
    - » V_{cutoff} (parabolic) = 3.53

- All else being equal,
  - Core diameter of GI-SM fiber can be $\sqrt{1+(2/g)}$ larger than SI-SM fiber
    - » Easier coupling
    - » Easier splicing
    - » Lower microbend losses

Fiber Parameters: Summary

- **Introduced**
  - **Fiber *core* and *cladding***
  - **Fiber guiding properties**
    - » **Total internal reflection**
    - » **Guiding by refractive index change**
  - **Step-index or Graded-index refractive index profile**
    - » **GI: modeled with power-law profile**

  - ***Modes* in fibers**
    - » ***Single-mode fiber***
      - ***Mode field diameter (MFD)***
      - ***Cutoff wavelength***
    - » **Multimode fiber**
      - ***V-parameter***
      - **Core radius, *a***
      - ***Numerical aperture*, NA**

Fiber Parameters: Summary (cont.)

- Multimode fibers
  - Pro:
    - » Moderate distances and/or data rates
    - » Easier coupling (larger core & NA)
  - Con:
    - » Lack extreme bandwidth capacity
    - » Mode mixing makes unpredictable behavior at joints

- Single-mode fibers
  - Present fiber of choice
  - Pro:
    - » High data rate-distance combinations
    - » Lower fiber attenuation
  - Con:
    - » Lower fabrication tolerances
    - » Lower coupling efficiency
    - » Lower misalignment tolerance at joints
    - » Increased susceptibility to bending and spooling losses

- Costs:
  - About equal
  - Readily available